*The Indian Journal of Agricultural Sciences* 95 (5): 503–508, May 2025/Article
https://doi.org/10.56093/ijas.v95i5.158756

# Effect of moisture management practices and zinc fertilization on growth, productivity and economics of pearl millet (*Pennisetum glaucum*) under pearl millet-mustard (*Brassica juncea*) system

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Received: 23 October 2024; Accepted: 27 January 2025

## ABSTRACT

Rainfed farming, crucial for India's food security, is severely impacted by moisture stress and nutrient deficiencies, particularly in semi-arid regions. The present study was carried out during the rainy (*kharif)* seasons of 2020 and 2021 at ICAR-Indian Agricultural Research Institute, New Delhi to evaluate the combined effects of moisture management practices and zinc fertilization on the productivity, quality, and economic yields of pearl millet (*Pennisetum glaucum* L.) within the pearl millet-mustard (*Brassica Juncea* L.) cropping system, a staple in India's dryland agriculture. The experiment was laid out in a split-plot design (SPD) replicated thrice. The main plot treatments focused on moisture conservation methods, including no mulch, straw mulch at 3 t/ha, Pusa hydrogel at 2.5 kg/ha, and Pusa hydrogel at 5 kg/ha. The sub-plot treatments addressed zinc fertilization, comprising no zinc application, soil application of 25 kg $ZnSO_4 \cdot 7H_2O$/ha, soil application of 12.5 kg $ZnSO_4 \cdot 7H_2O$/ha combined with a foliar spray of 0.5% $ZnSO_4 \cdot 7H_2O$ at the maximum tillering stage, and foliar sprays of 0.5% $ZnSO_4 \cdot 7H_2O$ at both the maximum tillering and before flowering stages. Results revealed that the applying Pusa hydrogel at 5 kg/ha substantially enhanced yield attributes, with the highest ear head length (28.5–29.2 cm) and weight (18.6–19.0 g). The application of zinc, specifically incorporating 12.5 kg/ha of $ZnSO_4 \cdot 7H_2O$ to the soil along with a foliar spray at the maximum tillering stage, significantly boosted yield by improving water absorption and enhancing drought resilience. Grain yields were highest with applying Pusa hydrogel @5 kg/ha (2.17–2.23 t/ha), while zinc fertilization increased grain zinc concentration by 15% and protein content by 10.84%. Economic analysis showed that Pusa hydrogel @5 kg/ha accrued the highest net returns, while 2.5 kg/ha dosage offered a cost-effective alternative for budget-conscious farmers. Therefore, it is recommended to apply Pusa hydrogel @2.5 or 5 kg/ha, combined with 12.5 kg/ha of $ZnSO_4 \cdot 7H_2O$ as a soil treatment, followed by a 0.5% foliar spray at the maximum tillering stage, for pearl millet cultivation within the pearl millet–mustard cropping system in western India to enhance crop performance, optimize resource use, and improve the economic sustainability of the cropping system.

**Keywords**: Dryland agriculture, Moisture management, Mulching, Pearl millet, Zinc fertilization

Rainfed farming, spanning 55% of India's cultivated land, is crucial for food security but faces productivity challenges due to moisture stress and nutrient deficiencies in semi-arid areas. These issues are acute in dryland farming systems, where erratic rainfall and frequent droughts result in water scarcity, leading to substantial reductions in crop yields (Venkateswarlu *et al.* 2011). Moisture stress, a key limiting factor, impacts the entire crop growth cycle, from germination to grain filling. To address this, strategies such as mulching, hydrogels, and conservation tillage that improve soil moisture retention and utilize residual moisture are vital for enhancing rainfed crop productivity.

Zinc (Zn) deficiency is another major challenge for dryland farming. Zinc is a critical micronutrient for plants, playing a vital role in enzyme activation, protein synthesis, and stress regulation (Cakmak 2008). Despite its importance, zinc deficiency is prevalent in Indian soils, especially in arid and semi-arid areas, adversely affecting crop yields and the nutritional quality of harvested produce (Shukla and Tiwari 2016). Crops like pearl millet, commonly grown in moisture-stressed environments, are particularly affected, as zinc deficiency exacerbates water scarcity impacts, leading to poor grain development and yield loss (Alloway 2008). Hassan *et al.* (2020) indicated that zinc application can enhance root growth and water uptake, enabling crops to better withstand drought. Combining zinc fertilization with moisture conservation techniques can significantly boost efficiency of productivity and resource utilization in rainfed

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systems, such as the pearl millet (*Pennisetum glaucum* L.)-mustard (*Brassica Juncea* L.) cropping system.

Pearl millet, a drought-tolerant crop, is cultivated during the *kharif* season, while mustard is grown in *rabi*, utilizing residual moisture from monsoon rains. Despite their resilience, suboptimal moisture management and zinc deficiency constrain their productivity (Parihar *et al.* 2012). Studies confirm that zinc fertilization improves yields and enhances drought tolerance by boosting water uptake efficiency and enzyme activity (Cakmak 2008). Thus, integrated approaches combining moisture conservation and zinc supplementation are crucial for enhancing the sustainability of this cropping system.

## MATERIALS AND METHODS

The present study was carried out during the rainy (*kharif)* seasons of 2020 and 2021 at ICAR-Indian Agricultural Research Institute, New Delhi. The soil exhibited a sandy loam texture with a *p*H ranging from 7.75–7.82, electrical conductivity (EC) between 0.24 and 0.36 dS/m, organic carbon content of 0.41–0.44%, available nitrogen (N) of 262–288 kg/ha, available phosphorus (P) of 15–17 kg/ha, potassium (K) of 245–269 kg/ha, and zinc (Zn) concentration of 0.63 mg/kg, measured at a soil depth of 0–15 cm (Lindsay and Norvell 1978). The experiment was conducted using a split-plot design (SPD) replicated three times. The treatments comprised moisture conservation practices as main plots, namely $M_0$, No mulch; $M_1$, Straw mulch at 3 t/ha; $M_2$, Pusa hydrogel at 2.5 kg/ha; $M_3$, Pusa hydrogel at 5 kg/ha. Zinc fertilization treatments were applied as sub-plot treatments, including $Z_0$, No zinc; $Z_1$, Soil application of 25 kg $ZnSO_4 \cdot 7H_2O$/ha; $Z_2$, Soil application of 12.5 kg $ZnSO_4 \cdot 7H_2O$/ha + foliar spray of 0.5% $ZnSO_4 \cdot 7H_2O$ at the maximum tillering stage; $Z_3$, Foliar sprays of 0.5% $ZnSO_4 \cdot 7H_2O$ at maximum tillering and before flowering stage. Tillage operations were carried out in the experimental units after sufficient rainfall was received. The pearl millet variety used was Pusa Composite-443, and sowing occurred on July 16, 2020, and July 12, 2021, at a row spacing of 30 cm and plant spacing of 15 cm. Before sowing, Pusa hydrogel was mixed with the soil and applied at a depth of 7–10 cm, as outlined in the proposed treatment. In the plots with mulching treatment, 3 t/ha of mustard crop residues were applied after thinning, and gap filling. The recommended fertilizer application included 40 kg N, 30 kg $P_2O_5$, and 30 kg $K_2O$/ha, applied as a basal dose at sowing using urea, diammonium phosphate (DAP), and muriate of potash (MOP), respectively. An additional 40 kg N/ha was applied as a top-dress 30 days after sowing (DAS). Zinc was applied according to the treatments, using zinc sulfate ($ZnSO_4 \cdot 7H_2O$) containing 21% Zn and 10% S. No lifesaving irrigations were given to the crop during either year. To reduce weed competition, a manual hand weeding was carried out at 25 DAS in both years, followed by a second-hand weeding to remove weeds that emerged later. Pearl millet grain and straw yields were determined by manually harvesting a net plot area, sun-drying the produce for three days, and then threshing it. The grains were cleaned after threshing, and the grain yield was recorded at a moisture content of 12%. Soil moisture content was measured at 30 and 60 days after sowing (DAS) and at harvest. Moisture content was determined based on oven-dry weight using the formula below:

$$\text{Soil moisture content (\%)} = \frac{\text{Wet weight } (W_1) - \text{Dry weight } (W_2)}{\text{Dry weight } (W_2)} \times 100$$

The crude protein content of pearl millet grains was determined by multiplying the nitrogen content by a factor of 6.25 (Prasad *et al.* 2006). Grain zinc concentration was measured using atomic absorption spectroscopy (AAS) (Prasad *et al.* 2006). After grinding and oven-drying, grain samples underwent acid digestion, and the solution was analyzed @213.9 nm, with zinc concentration expressed as mg/kg grain.

The economic analysis was worked out using the following formulae

$$\text{Net returns} = \text{Gross returns} - \text{cost of cultivation}$$

$$\text{Net BCR} = \frac{\text{Net returns}}{\text{Total cost of cultivation}}$$

Statistical analysis of field and laboratory data was performed using the standard analysis of variance (ANOVA) method, with significance evaluated through the F-test as described by Gomez and Gomez (1984). The standard error of means (SEM±) and the critical difference ($P<0.05$) were calculated to determine significant differences among treatment means.

## RESULTS AND DISCUSSION

*Soil moisture content*: The study found that soil moisture content in the pearl millet crop of the pearl millet-mustard system was significantly affected by moisture management and zinc fertilization during different growth stages at soil depths of 0–15 cm and 15–30 cm over the two years of the study (Fig. 1). Further, soil moisture decreased over time, with the highest levels at the initial growth stage (0–30 DAS) and the lowest at harvest. The deeper soil layer (15–30 cm) retained more moisture than the surface layer (0–15 cm) throughout the study. Pusa hydrogel application (5 kg/ha) ($M_3$) resulted in the highest soil moisture levels across all growth stages. For instance, @30 DAS, soil moisture with Pusa hydrogel was 14.8% and 18.3% at 0–15 cm in 2020 and 2021, respectively, and 15.7% and 18.9% at 15–30 cm. The no-mulch treatment had the lowest soil moisture, decreasing to 4.64% and 5.36% at harvest. Zinc fertilization also improved soil moisture, with the combination of soil-applied $ZnSO_4 \cdot 7H_2O$ @12.5 kg/ha with a foliar spray of 0.5% $ZnSO_4 \cdot 7H_2O$ at the maximum tillering stage ($Z_2$) resulting in the highest levels. At 60 DAS, this treatment resulted in soil moisture of 12.1% and 14.9% at 0–15 cm in 2020 and 2021, respectively, and even higher levels at 15–30 cm. The control (no zinc) had the lowest soil moisture.

*Yield attributes of pearl millet*: The data demonstrated

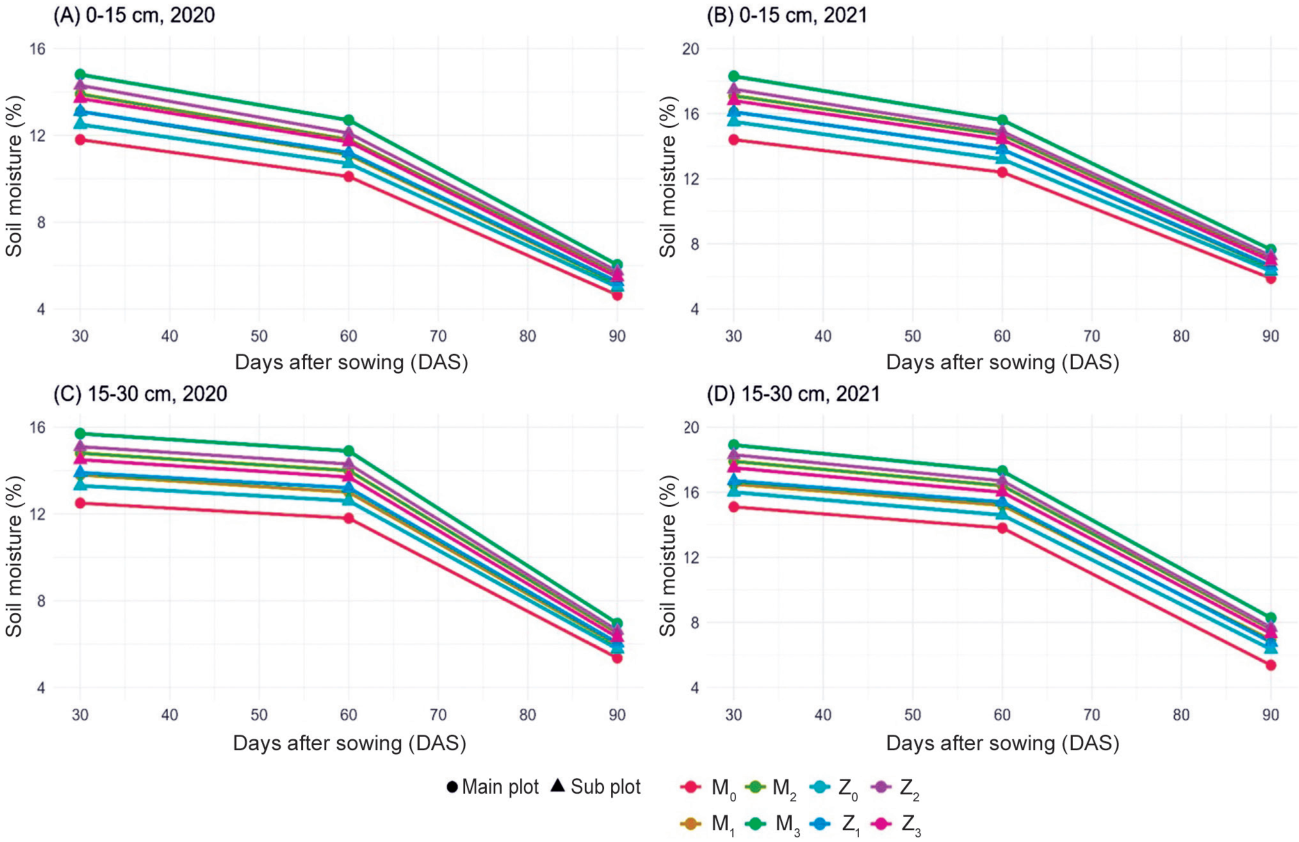


Fig. 1 Effect of moisture management practices and zinc fertilization on soil moisture at soil depth of 0–15 cm and 15–30 cm in pearl millet.
Treatment details are given under Materials and Methods.

that moisture management practices and zinc fertilization play a pivotal role in enhancing yield attributes of pearl millet (Table 1). Notably, the applying Pusa hydrogel at 5 kg/ha ($M_3$) resulted in the highest ear head length (28.5 cm and 29.2 cm) and weight (18.6 g and 19.0 g) during both years of the study, outperforming no-mulch treatment.

Table 1 Influence of moisture management practices and zinc fertilization on yield attributes of pearl millet

| Treatment | Ear head length (cm) | | | Ear head girth (cm) | | | Ear head weight (g) | | | 1000-grain weight (g) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled |
| Moisture management practices | | | | | | | | | | | | |
| $M_0$ | 23.9 | 24.5 | 24.17 | 8.58 | 8.77 | 8.67 | 15.3 | 15.7 | 15.50 | 8.06 | 8.13 | 8.09 |
| $M_1$ | 25.6 | 26.2 | 25.89 | 8.69 | 8.88 | 8.78 | 16.5 | 16.8 | 16.65 | 8.18 | 8.26 | 8.22 |
| $M_2$ | 27.2 | 27.8 | 27.49 | 8.71 | 8.89 | 8.80 | 17.7 | 18.1 | 17.88 | 8.30 | 8.37 | 8.33 |
| $M_3$ | 28.5 | 29.2 | 28.87 | 8.88 | 9.06 | 8.97 | 18.6 | 19.0 | 18.79 | 8.39 | 8.46 | 8.42 |
| SEm± | 0.46 | 0.47 | 0.32 | 0.16 | 0.17 | 0.11 | 0.30 | 0.30 | 0.21 | 0.15 | 0.15 | 0.11 |
| LSD ($P$=0.05) | 1.57 | 1.61 | 0.99 | NS | NS | NS | 1.02 | 1.04 | 0.64 | NS | NS | NS |
| Zinc fertilization | | | | | | | | | | | | |
| $Z_0$ | 24.4 | 25.0 | 24.70 | 8.49 | 8.67 | 8.57 | 15.9 | 16.2 | 16.00 | 8.07 | 8.13 | 8.18 |
| $Z_1$ | 25.8 | 26.5 | 26.16 | 8.66 | 8.84 | 8.75 | 16.6 | 17.0 | 16.83 | 8.18 | 8.24 | 8.31 |
| $Z_2$ | 28.0 | 28.7 | 28.32 | 8.92 | 9.12 | 9.01 | 18.2 | 18.6 | 18.35 | 8.37 | 8.45 | 8.41 |
| $Z_3$ | 26.9 | 27.6 | 27.24 | 8.79 | 8.98 | 8.88 | 17.5 | 17.8 | 17.64 | 8.32 | 8.39 | 8.35 |
| SEm± | 0.36 | 0.37 | 0.25 | 0.12 | 0.13 | 0.84 | 0.23 | 0.24 | 0.16 | 0.12 | 0.12 | 0.08 |
| LSD ($P$=0.05) | 1.03 | 1.06 | 0.79 | NS | NS | NS | NS | 0.69 | 0.51 | NS | NS | NS |
| Interaction | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

Treatment details are given under Materials and Methods.

Hydrogels like Pusa hydrogel reduce water stress during critical growth stages, allowing the plant to better allocate resources for reproductive development, such as ear head formation, which was reflected in the observed increase in ear head length and weight. The combination of soil-applied $ZnSO_4 \cdot 7H_2O$ @12.5 kg/ha with a foliar spray of 0.5% $ZnSO_4 \cdot 7H_2O$ at the maximum tillering stage ($Z_2$) significantly increased ear head length (28.0 cm and 28.7 cm) and weight (18.2 g and 18.6 g) compared to other zinc treatments. Similarly, studies have shown that foliar zinc application at critical growth stages, such as flowering, can enhance reproductive growth and grain filling by improving photosynthetic efficiency and regulating auxin synthesis, which may explain the improved ear head length and weight observed in this study (Alloway 2008, Hafeez *et al.* 2013). While girth and 1000-grain weight were not significantly impacted, plots with moisture and zinc treatments generally performed better than control. These findings emphasize the critical influence of both moisture and zinc in optimizing pearl millet yield attributes and productivity.

*Yields of pearl millet*: The grain yield of pearl millet showed significant variation across moisture management practices, with the highest yields (2.17 and 2.23 t/ha) were observed with the applying of Pusa hydrogel @5 kg/ha ($M_3$) during 2020 and 2021, respectively (Table 2). In contrast, the no-mulch treatment consistently produced the lowest yields. This aligns with previous research indicating that superabsorbent hydrogels improve soil water-holding capacity, prolong soil moisture availability during dry periods, and enhance plant water use efficiency, ultimately leading to higher crop yields (Vedovello *et al.* 2024, Patra *et al.* 2022). Similarly, studies have shown that hydrogels improve soil moisture content and water use efficiency under water-limited conditions, boosting crop productivity (Guilherme *et al.* 2015). Pusa hydrogel mitigates moisture stress during critical stages like grain filling, maximizing yield potential. The Pusa hydrogel @5 kg/ha ($M_3$) treatment also boosted grain yield by 20.5–21.9% and straw yield by 16.25–18.6% compared to the no-mulch treatment.

Zinc fertilization, specifically the soil application of $ZnSO_4 \cdot 7H_2O$ @12.5 kg/ha followed by a foliar spray of 0.5% $ZnSO_4 \cdot 7H_2O$ at the maximum tillering stage ($Z_2$), significantly boosted both grain and straw yields. Zinc fertilization enhanced grain yield by 160–181 kg/ha and straw harvest by 251–272 kg/ha. Zinc fertilization increased zinc accessibility to plants in cured plots compared to control (no Zn) plots, eventually resulting in distinguished biomass production and yields (Shivay *et al.* 2015, Shivay *et al.* 2016, Ghasal *et al.* 2017). Overall, moisture management and zinc fertilization had considerable effects on grain, straw, and biological yields, though the harvest index remained unaffected.

*Nutritional parameters of pearl millet*: The applying of Pusa hydrogel @5 kg/ha ($M_3$) markedly increased the protein contents of pearl millet, with values of 10.59% in 2020 and 10.84% in 2021 (Table 2). The improved soil moisture retention from the hydrogel facilitated better

Table 2 Influence of moisture management practices and zinc fertilization on yield and nutritional quality parameters of pearl millet

| Treatment | Grain yield (t/ha) | | | Straw yield (t/ha) | | | Biological yield (t/ha) | | | Grain Zn concentration (mg/kg) | | | Protein (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled |
| Moisture management practices | | | | | | | | | | | | | | | |
| $M_0$ | 1.78 | 1.85 | 1.81 | 6.14 | 6.39 | 6.26 | 7.91 | 8.24 | 8.07 | 30.01 | 31.34 | 30.67 | 9.34 | 9.59 | 9.47 |
| $M_1$ | 1.90 | 1.98 | 1.93 | 6.60 | 6.89 | 6.74 | 8.50 | 8.86 | 8.68 | 32.81 | 34.27 | 33.54 | 10.01 | 10.25 | 10.12 |
| $M_2$ | 2.06 | 2.11 | 2.08 | 7.05 | 7.33 | 7.18 | 9.09 | 9.43 | 9.26 | 34.01 | 35.51 | 34.76 | 10.37 | 10.62 | 10.49 |
| $M_3$ | 2.17 | 2.23 | 2.19 | 7.28 | 7.63 | 7.45 | 9.44 | 9.84 | 9.64 | 35.38 | 36.95 | 36.16 | 10.59 | 10.84 | 10.71 |
| SEm± | 0.04 | 0.04 | 0.02 | 0.12 | 0.13 | 0.08 | 0.16 | 0.16 | 0.11 | 0.55 | 0.57 | 0.39 | 0.18 | 0.19 | 0.13 |
| LSD ($P$=0.05) | 0.12 | 0.13 | 0.07 | 0.41 | 0.43 | 0.26 | 0.53 | 0.55 | 0.33 | 1.88 | 1.96 | 1.21 | 0.62 | 0.63 | 0.39 |
| Zinc fertilization | | | | | | | | | | | | | | | |
| $Z_0$ | 1.82 | 1.85 | 1.83 | 6.33 | 6.59 | 6.45 | 8.15 | 8.43 | 8.28 | 24.51 | 25.60 | 25.05 | 9.58 | 9.81 | 9.69 |
| $Z_1$ | 1.94 | 1.98 | 1.96 | 6.61 | 6.89 | 6.75 | 8.53 | 8.86 | 8.69 | 31.26 | 32.65 | 31.95 | 10.01 | 10.24 | 10.12 |
| $Z_2$ | 2.13 | 2.22 | 2.17 | 7.22 | 7.54 | 7.37 | 9.34 | 9.75 | 9.54 | 39.12 | 40.85 | 39.98 | 10.52 | 10.78 | 10.65 |
| $Z_3$ | 2.03 | 2.11 | 2.07 | 6.91 | 7.22 | 7.06 | 8.93 | 9.33 | 9.13 | 37.32 | 38.98 | 38.14 | 10.23 | 10.47 | 10.35 |
| SEm± | 0.03 | 0.03 | 0.02 | 0.10 | 0.10 | 0.07 | 0.12 | 0.13 | 0.09 | 0.46 | 0.48 | 0.33 | 0.14 | 0.14 | 0.10 |
| LSD ($P$=0.05) | 0.08 | 0.09 | 0.06 | 0.27 | 0.28 | 0.20 | 0.35 | 0.36 | 0.26 | 1.34 | 1.40 | 1.02 | 0.40 | 0.41 | 0.30 |
| Interaction | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

Treatment details are given under Materials and Methods.

Table 3 Influence of moisture management practices and zinc fertilization on economics of pearl millet

| Treatment | Cost of cultivation (₹ ×$10^3$/ha) | | Gross returns (₹ ×$10^3$/ha) | | | Net returns (₹ ×$10^3$/ha) | | | Net benefit-cost ratio | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2020 | 2021 | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled | 2020 | 2021 | Pooled |
| Moisture management practices | | | | | | | | | | | |
| $M_0$ | 23.01 | 24.09 | 47.32 | 52.37 | 49.85 | 23.31 | 28.29 | 26.30 | 1.06 | 1.18 | 1.12 |
| $M_1$ | 25.06 | 25.87 | 50.73 | 56.04 | 53.38 | 25.67 | 30.17 | 27.92 | 1.03 | 1.17 | 1.10 |
| $M_2$ | 25.51 | 26.59 | 54.72 | 59.87 | 57.30 | 29.23 | 33.31 | 31.27 | 1.15 | 1.26 | 1.20 |
| $M_3$ | 28.01 | 29.09 | 57.50 | 62.89 | 60.20 | 29.51 | 33.82 | 31.67 | 1.06 | 1.17 | 1.11 |
| SEm± | - | - | 0.90 | 0.99 | 0.67 | 0.45 | 0.53 | 0.35 | 0.02 | 0.03 | 0.01 |
| LSD (*P*=0.05) | - | - | 3.12 | 3.43 | 2.06 | 1.57 | 1.82 | 1.07 | 0.07 | 0.08 | 0.04 |
| Zinc fertilization | | | | | | | | | | | |
| $Z_0$ | 24.33 | 25.37 | 48.56 | 52.73 | 50.65 | 23.55 | 27.38 | 25.82 | 0.97 | 1.08 | 1.04 |
| $Z_1$ | 26.74 | 27.65 | 51.42 | 56.15 | 53.79 | 24.71 | 28.52 | 26.62 | 0.93 | 1.04 | 0.98 |
| $Z_2$ | 25.76 | 26.65 | 56.46 | 62.59 | 59.53 | 30.70 | 35.94 | 33.32 | 1.20 | 1.35 | 1.27 |
| $Z_3$ | 24.78 | 25.95 | 53.83 | 59.70 | 56.76 | 29.05 | 33.75 | 31.40 | 1.18 | 1.31 | 1.24 |
| SEm± | - | - | 0.71 | 0.78 | 0.53 | 0.37 | 0.43 | 0.28 | 0.02 | 0.02 | 0.01 |
| LSD (*P*=0.05) | - | - | 2.07 | 2.28 | 1.63 | 1.08 | 1.26 | 0.88 | 0.05 | 0.05 | 0.03 |
| Interaction | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

Treatment details are given under Materials and Methods.

nutrient uptake, enhancing protein synthesis by ensuring adequate nitrogen absorption during critical growth stages (Kusvuran *et al.* 2021). Additionally, these treatments had a significant effect on zinc concentration of grain, with the applying 5 kg/ha Pusa hydrogel, zinc levels elevated to 35.38 mg/kg in 2020 and 36.95 mg/kg in 2021. Similarly, soil application of $ZnSO_4{\cdot}7H_2O$ @12.5 kg/ha, followed by a foliar spray of 0.5% $ZnSO_4{\cdot}7H_2O$ at the maximum tillering stage ($Z_2$), led to increased protein levels compared to other zinc fertilization treatments. Further, soil application of $ZnSO_4{\cdot}7H_2O$ @12.5 kg/ha, followed by a foliar spray of 0.5% $ZnSO_4{\cdot}7H_2O$ at the maximum tillering stage ($Z_2$) resulted in even higher concentrations of zinc 39.12 mg/kg in 2020 and 40.85 mg/kg in 2021. Previous studies have shown that zinc application can improve the nutritional quality of cereals, including pearl millet, by increasing protein and micronutrient content (Shivay *et al.* 2014).

*Economics*: During the 2nd year of the experiment, the cost of cultivation increased across all treatments evaluated to the first year (Table 3). Gross returns were higher in the second year, with the applying Pusa hydrogel at 5 kg/ha ($M_3$) yielding gross returns of ₹57.50 and ₹62.89 × $10^3$/ha in 2020 and 2021, respectively, significantly outperforming other moisture management treatments. Similarly, the maximum net returns were achieved with the applying Pusa hydrogel @5 kg/ha ($M_3$), amounting to ₹29.51 and ₹33.82 × $10^3$/ha during the two years, with net returns being higher in the second year. This aligns with findings from other studies, which have reported that the use of hydrogels can lead to substantial increases in crop yields, thus providing farmers with a more profitable return on their investments (Kumawat *et al.* 2023). In contrast, the applying of Pusa hydrogel at 2.5 kg/ha resulted in a higher net benefit-cost ratio. It suggests that while this lower dosage (2.5 kg/ha) ($M_2$) may result in slightly lower gross and net returns compared to the 5 kg/ha application ($M_3$), it could still be a more cost-effective option for farmers with budget constraints. This aligns with the concept of optimizing resource use in agriculture, where applying the minimum effective dose can maximize profit margins (Jha 2020, Paramesh *et al.* 2023). Overall, hydrogel applications can improve soil moisture availability and reduce irrigation frequency, which ultimately contributes to better crop performance (Rathore *et al.* 2020). Furthermore, cultivation costs for zinc-treated plots were elevated, particularly with the soil application of $ZnSO_4{\cdot}7H_2O$ @25 kg/ha. The treatment involving soil application of $ZnSO_4{\cdot}7H_2O$ @12.5 kg/ha, followed by a 0.5% $ZnSO_4{\cdot}7H_2O$ foliar spray at the maximum tillering stage ($Z_2$), resulted in the maximum gross returns (₹56.46 × $10^3$/ha and ₹62.59 × $10^3$/ha) and net returns (₹30.70 × $10^3$/ha and ₹35.94 × $10^3$/ha) in both years. In contrast, plots without zinc application recorded lower gross returns, net returns, and net benefit-cost ratios. Analogous observations were noted by Ghatak *et al.* (2005) and Ghasal *et al.* (2015).

This present study highlights the critical role of moisture management and zinc fertilization in enhancing the productivity, nutritional quality, and profitability of pearl millet in a pearl millet-mustard cropping system. Specifically, the applying of Pusa hydrogel @5 kg/ha proved highly effective in alleviating water stress and optimizing resource use, thus improving yield attributes. Additionally, zinc fertilization, using soil-applied $ZnSO_4{\cdot}7H_2O$ at 12.5 kg/ha with a foliar spray of 0.5% $ZnSO_4{\cdot}7H_2O$ at the maximum tillering stage, significantly boosted both grain and straw yields, along with increasing grain zinc concentration and protein content. Economic analysis showed that Pusa hydrogel @5 kg/ha generated the highest gross and net returns, while the 2.5 kg/ha application rate offered a more cost-effective alternative for farmers with resource constraints. These findings underscore the potential of integrating moisture management and zinc fertilization as a sustainable intensification strategy for pearl millet, especially in water-scarce environments.

REFERENCES

Alloway B J. 2008. *Zinc in soil and crop nutrition*. 2nd edn, pp. 223–25. International Zinc Association and International Fertilizer Association, Belgium and Paris, France.

Cakmak I. 2008. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification. *Plant and Soil* **302**: 1–17.

Ghasal P C, Shivay Y S and Pooniya V. 2015. Response of basmati rice (*Oryza sativa*) varieties to zinc fertilization. *Indian Journal of Agronomy* **60**(3): 403–09.

Ghasal P C, Shivay Y S, Pooniya V, Choudhary M and Verma R K. 2017. Response of wheat genotypes to zinc fertilization for improving productivity and quality. *Archives of Agronomy and Soil Science* **63**(11): 1597–612.

Ghatak R, Jana P K, Sounda G, Ghosh R K and Bandyopadhyay P. 2005. Response of transplanted rice to zinc fertilization at farmer's field on red and laterite soils of West Bengal. *Journal of Interacademicia* **9**(2): 231–34.

Gomez K A and Gomez A A. 1984. *Statistical Procedures for Agricultural Research.* 2nd edn, pp. 680. John Wiley and Sons, New York

Guilherme M R, Aouada F A, Fajardo A R, Martins A F, Paulino A T, Davi M F T, Rubira A F and Muniz E C. 2015. Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioners and nutrient carriers: A review. *European Polymer Journal* **72**: 365–85.

Hafeez B, Khanif Y M and Saleem M. 2013. Role of zinc in plant nutrition-A review. *American Journal of Experimental Agriculture* **3**(2): 374–91.

Hassan M U, Aamer M, Chattha M U, Haiying T, Shahzad B, Barbanti L, Liu Y and Guoqin H. 2020. The critical role of zinc in plants facing the drought stress. *Agriculture* **10**: 0396.

Jha A K. 2020. Optimizing nutrient management for sustainable crop production: A review. *Agronomy* **10**(2): 250.

Kumawat P, Ram M, Kumar P, Kumari V and Khedwal R S. 2023. Maximizing productivity, profitability, and water use efficiency in Indian mustard (*Brassica juncea*) through hydrogel and salicylic acid. *The Indian Journal of Agricultural Sciences* **94**(2): 145–49.

Kusvuran S, Dasgan H Y and Abak K. 2021. The influence of drought stress on growth, mineral nutrition, and protein content of some cowpea (*Vigna unguiculata* L. *Walp*.) genotypes. *Legume Research-An International Journal* **44**(1): 16–21.

Lindsay W L and Norvell W A. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal* **42**(3): 421–28.

Paramesh V, Kumar P, Bhagat T, Nath A J, Manohara K K, Das B, Desai B F, Jha P K and Vara Prasad P V. 2023. Integrated nutrient management enhances yield, improves soil quality, and conserves energy under the lowland rice–rice cropping system. *Agronomy* **13**(6): 1557.

Parihar C M, Rana K S, Jat M L, Jat S L, Parihar M D, Kantwa S R and Singh D K. 2012. Carbon footprint and economic sustainability of pearl millet-mustard system under different tillage and nutrient management practices in moisture stress conditions. *African Journal of Microbiology Research* **6**(23): 5052–61.

Patra S K, Poddar R, Brestic M, Acharjee P U, Bhattacharya P, Sengupta S, Pal P, Bam N, Biswas B, Barek V and Ondrisik P. 2022. Prospects of hydrogels in agriculture for enhancing crop and water productivity under water deficit condition. *International Journal of Polymer Science* pp. 4914836.

Prasad R, Shivay Y S, Kumar D and Sharma S N. 2006. *Learning by Doing Exercises in Soil Fertility–A Practical Manual for Soil Fertility*. ICAR-Indian Agricultural Research Institute, New Delhi, India.

Rathore S S, Shekhawat K, Babu S and Singh V K. 2020. Mitigating moisture stress in *Brassica juncea* through deficit irrigation scheduling and hydrogel in Ustocherpts soils of semi-arid India. *Heliyon* **6**: e05786.

Shivay Y S, Prasad R and Pal M. 2014. Zinc fortification of cereals for enhancing productivity and bioavailability: A review. *Indian Journal of Agronomy* **59**(1): 15–23.

Shivay Y S, Prasad R, Kaur R and Pal M. 2016. Relative efficiency of zinc sulphate and chelated zinc on zinc biofortification of rice grains and zinc use-efficiency in Basmati rice. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences* **86**: 973–84.

Shivay Y S, Prasad R, Singh R K and Pal M. 2015. Relative efficiency of zinc-coated urea and soil and foliar application of zinc sulphate on yield, nitrogen, phosphorus, potassium, zinc and iron biofortification in grains and uptake by *Basmati* rice (*Oryza sativa* L.). *Journal of Agricultural Science* **7**(2): 161–173.

Shukla A K and Tiwari P K. 2016. Micro and secondary nutrients and pollutant elements research in India. *Coordinator's report.* AICRP on Micro- and Secondary Nutrients and Pollutant Elements in Soils and Plants, ICAR-Indian Institute of Soil Science, Bhopal, pp. 1–196.

Vedovello P, Sanches L V, Teodoro G S, Majaron V F, Bortoletto-Santos R, Ribeiro C and Putti F F. 2024. An overview of polymeric hydrogel applications for sustainable agriculture. *Agriculture* **14**(6): 840.

Venkateswarlu B, Singh A K, Prasad Y G, Chary R G, Rao S Ch, Rao K V, Ramana D B V and Rao V U M. 2011. District level contingency plans for weather aberrations in India. Central Research Institute for Dryland Agriculture, Natural Management Division, Indian Council of Agricultural Research, Hyderabad.